PLOS SUSTAINABILITY AND TRANSFORMATION

RESEARCH ARTICLE

# Checklist and reporting framework to support documentation and communication of GIS-based Multi-Criteria Evaluation (MCE) models for aquaculture site selection

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## Abstract

Geographic Information Systems (GIS) are frequently used when conducting site suitability and site selection studies for aquaculture because the factors influencing the suitability of an area typically contain a spatial element. Multi-criteria evaluation (MCE), often based on the Weighted Linear Combination (WLC) method, is commonly used in aquaculture as it allows the combination of numerous and often conflicting interdisciplinary criteria and the evaluation of the trade-offs between them. GIS-based MCE models can be implemented in different ways according to the modelling objectives, but a lack of transparency and unclear information on characteristics of the model and output(s) can affect their use in real-world decisions. This study analysed 71 scientific articles that developed and used GIS-based MCE for aquaculture site selection and site suitability modelling. The articles were identified using the PRISMA systematic review protocol and covered a wide range of locations, species, and production systems. Data on the reported model characteristics were extracted from the scientific articles and analysed to identify trends, similarities, and differences in the information provided within the studies. The analysis revealed inconsistencies in how models were described, with some articles missing important information that could limit their use for many aquaculture planning decisions. Based on these findings, a checklist and reporting framework were produced that can be used to ensure important information is easily accessible alongside GIS-based MCE models and their outputs. The checklist and reporting framework can act as a template to provide clear and consistent documentation that will facilitate the use of models and outputs by end users who may not have been involved in the modelling process and are unfamiliar with the technical aspects.

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## Author summary

The need for sustainable food production is a major societal challenge and transformative changes are urgently required across the world to meet accelerating demands for affordable and nutritious food. Aquaculture has been highlighted as a key route to increased

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food production, but expansion of the sector will depend on the availability of suitable sites. Models developed using Geographic Information Systems (GIS) are often used to assess the suitability of a location for aquaculture development. However, in this study, following analysis of 71 published articles, we show that there are many ways of reporting model structures and results, which could affect usability of model outputs and limit potential knowledge exchange. To bridge the gap between research and real-world applications, we have developed a checklist and reporting framework that can support a more standardised approach to communication and documentation. Our work encourages a more transparent approach to data-driven aquaculture planning that would minimise conflicts with other users and resources by using clear and consistent reporting, ensuring information is easily accessible. This work is significant since transformative actions will involve complex decisions so there must be clear evidence that shows the route behind choices.

## 1. Introduction

The Food and Agricultural Organization of the United Nations [1] have stated that aquaculture needs to undergo an "*acceleration of transformative changes in policy*, *management*, *innovation and investment*" in order to increase its vital contribution to global food and nutrition security in a responsible, sustainable and equitable manner. Significant increases in production will require sustainable intensification of existing sites as well as the development of new farming locations. Responsible planning for the determination of new, favourable areas for aquaculture is imperative for sustainable development of the sector [2,3]. However this is not an easy task and FAO also recognise that a lack of adequate information and data is a bottleneck for policymaking and planning [1], potentially hindering transformative action in many areas and affecting the ability of aquaculture to optimise its contribution to the global food system. The suitability of an area for aquaculture depends on a range of ecological, biological, economic, and social criteria and the aquaculture sector, planners and policymakers need information on these criteria to help identify the most suitable locations for development. Some areas are more suitable for aquaculture than others, and certain areas will be unavailable as they should be prioritised for other activities or remain undeveloped. With copious numbers of criteria to consider, and potentially difficult trade-offs to be made, use of decision-support tools becomes essential [2–5]. Many of the criteria are inherently spatial, varying across areas and locations, thus spatial modelling is key in the assessment and identification of areas with potential for aquaculture [2]. Spatial modelling also provides the means to support an integrated approach to management, which is essential for maximizing the use of aquatic resources while minimizing user conflict [6].

One of the most common methods of conducting spatial modelling is using Geographic Information Systems (GIS). GIS is a computer system used to capture, encode, store, analyze and display geospatial data, and is frequently used in many industries [7,8]. For aquaculture site suitability analyses, the advent of GIS allowed the transition away from time-consuming and subjective site selection studies using individual maps, to a more efficient, systematic method that allows users to perform multiple assessments in a more efficient and objective manner [9]. GIS is favoured for this type of work because it allows the integration of different types and sources of data, providing the flexibility needed to consolidate real-world information. The benefits of using spatial modelling for aquaculture have been recognized by many stakeholders, which has led to an increased interest in the use of GIS to support planning decisions [4,10,11]. To date, there is an abundance of scientific articles investigating site suitability for a range of areas, species, and production systems across the globe. Over a third of GIS applications in aquaculture research are for site selection purposes [4], and many of the GIS-based aquaculture site selection models use the multi-criteria evaluation (MCE) method [12–14].

While GIS supplies the framework to perform spatial analyses, the MCE method provides a means for managing and combining numerous spatial criteria [15,16]. Other terms for MCE include multi-criteria analysis (MCA), multi-criteria decision analysis (MCDA) and spatial multi-criteria evaluation (SMCE). Though there are several ways to develop and implement spatial models using GIS, the MCE method, particularly the Weighted Summation or Weighted Linear Combination (WLC), is commonly used for aquaculture site suitability and site selection studies because it involves the consideration of trade-offs between criteria [3]. When used in a spatial context, the MCE method facilitates the organization of spatial data layers representing criteria of interest into a model framework using logical groups or submodels, allows the relative importance of criteria to be accounted for by assigning weights, and combines potentially adverse criteria to find suitable solutions [16]. Fig 1 provides a simple overview of the GIS-based MCE process for aquaculture site selection. Both the qualitative and quantitative outputs produced by a MCE provide an intuitive output that can be easily understood and used by decision makers [12]. Since MCE can be used to examine complex questions and trade-offs across interdisciplinary boundaries it is used for many different aspects of sustainable development beyond aquaculture [17]. Other examples of spatial modelling with MCE include identification of locations for landfill sites [18,19], desalination plants [20], and renewable energy facilities [21,22]. Dedicated MCE modules and extensions are even included in some GIS software [23]. Although the focus of this paper is the use of MCE within a spatial context for aquaculture site selection, there are other non-spatial applications, for example Latinopoulos et al. [24] used multicriteria analysis to compare alternative production scenarios for mussel farming in Greece. See Vergara-Solana et al. [25] for a detailed review of the use of multicriteria decision-making in aquaculture.

Aquaculture site selection studies that use MCE within GIS models follow some common steps (Fig 1), but the data and model structure are not standardised, which leads to different approaches and applications [26–29]. Flexibility in model development is an advantage as developers can tailor the models to their specific needs. Forcing a universally applicable and standardised modelling approach for aquaculture site selection with defined data inputs and

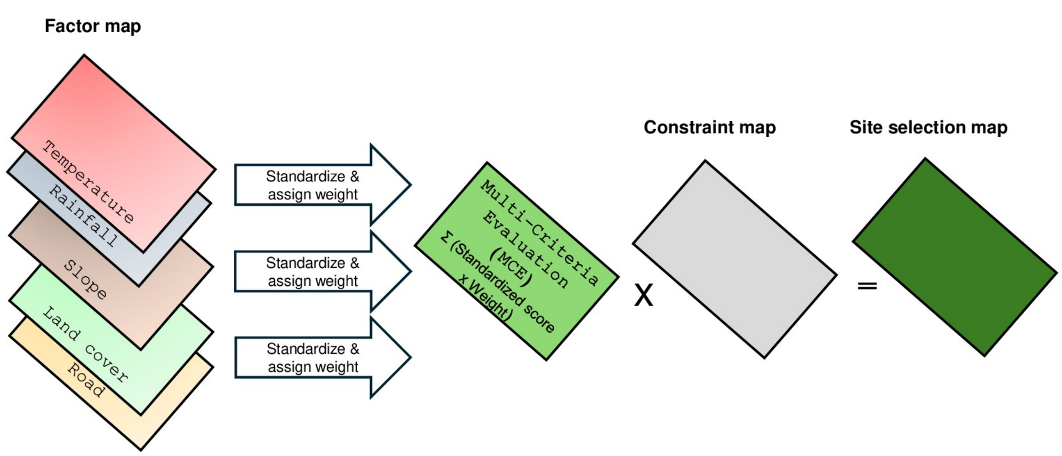


**Fig 1. Illustration of a simple GIS-based MCE process for aquaculture site selection.**

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weightings would be challenging, and would also severely limit real-world use as the desired site criteria and relative importance depends on the important locational characteristics, species requirements and particular expectations for the site [3,13]. However, the potential for infinite model structures creates complexity which may hinder use for real-world decision making, which is an issue as there is often a gap between GIS model development and its use as a decision support tool by industry and related stakeholders [4]. To bridge this gap, model developers must consider how models are communicated to end users [30]. End users, whether affiliated with aquaculture companies, regulatory authorities, or other decision-making organizations, do not need to be involved in every step of model development, but do need sufficient information to understand what the model represents and how it was achieved. The absence of common reporting protocols for aquaculture site suitability studies could be a contributing factor to the gap between model development and its use as a decision support tool. This is not an issue confined to the aquaculture sector and lack of transparency and unclear model descriptions have been identified as a major limitation to using models in real-world decision making, however improved documentation and clearer reporting can help bridge the gap [31,32].

Given the major societal challenges facing the world and the complexities of balancing human well-being, economic prosperity, and environmental sustainability, it is critical that decision-support tools are effectively communicated to end users to encourage responsible and transformative action. Transformative action requires major decisions that will inevitably involve trade-offs that must be acknowledged and justified with robust evidence and information. The rationale behind decisions must be clear to those directly involved (e.g., industry, local communities, and other resource users) as well as wider society. Specifically, decision-support models should be reported in a way that provides an understanding of the underlying data, the model structure, and the modelling process while also increasing transparency and facilitating trust in the decisions made. Although there have been reviews and analyses on the use of GIS-based models for aquaculture [4,5,10,12], including a specific focus on MCE [14], we are not aware of any study that has focused explicitly on how GIS-based MCE models are reported and how easily information can be extracted by readers. Accordingly, there are knowledge gaps surrounding how important characteristics of GIS-based MCE models for aquaculture are reported in the scientific literature. Furthermore, to our knowledge, there are no commonly used reporting protocols for aquaculture site selection studies which raises a hypothesis that information on the data, model structure, modelling processes and other important considerations are not consistently reported.

The aim of this study was to analyse how GIS-based MCE models are described in aquaculture site suitability and site selection studies and from this develop a checklist and reporting framework to improve documentation. The first step involved examining the characteristics of a sample of peer-reviewed publications that have used spatial modelling and the MCE method for aquaculture site suitability and site selection. Data on key features were extracted from the scientific articles and analysed to identify trends, similarities, and differences in reporting and information provided within the studies. The effort required to find, extract, and synthesise relevant information from each article and the clarity of the information was used to guide the development of a checklist that will provide a clearer and more standardised description of a model and outputs when used.

## 2. Methods

### 2.1. Literature search

A search was conducted on academic research databases to identify articles that were relevant to the scope of the study. The screening and review process followed the Preferred Reporting

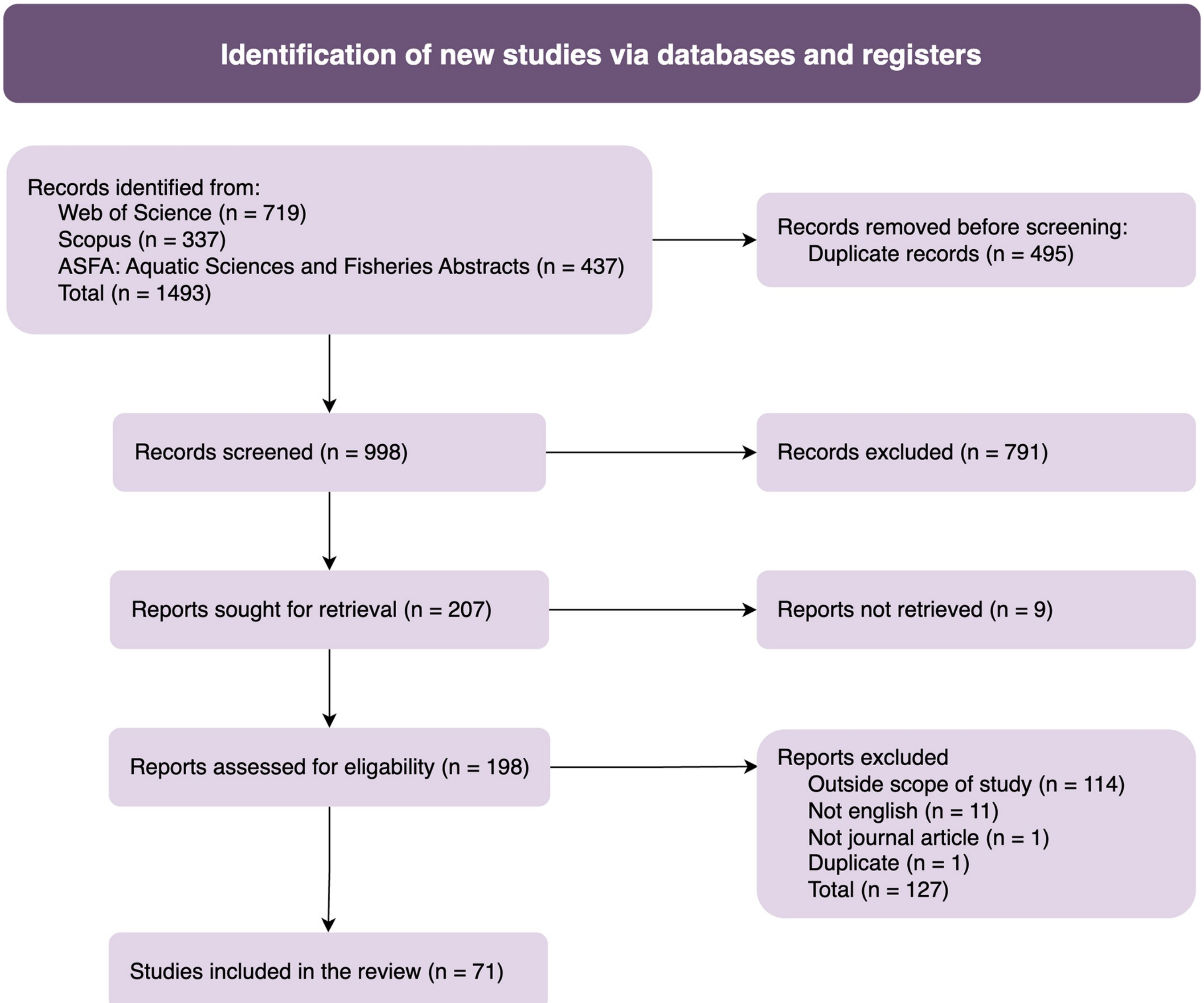


**Fig 2. The process flow for performing a systematic review to identify articles using both spatial modelling and the MCE method to conduct site suitability studies, in the form recommended by the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) 2020 protocol [33,34].**

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Items for Systematic reviews and Meta-Analysis (PRISMA) protocol, which was created as a tool to help standardize and improve transparency in reviews and meta-analyses [33]. PRISMA was initially used for clinical studies but has since been adopted by numerous fields, and in addition to a number of its extensions, is now one of the most frequently used methods for conducting systematic reviews and meta-analyses [34]. This study used PRISMA 2020 (Fig 2), the most up-to-date protocol, which is similar to the original 2009 protocol apart from the slight change in terminology. This makes it more inclusive for a wide range of applications and potential uses of the information [34].

The aim was to use inclusive keywords to retrieve a diverse set of studies that included any form of aquaculture across the world. Although any type of aquaculture was acceptable and

**Table 1. Characteristics required of the studies for inclusion in the analysis and the corresponding key words used in the database searches aimed at extracting them.**

| Inclusion Criteria | |
|---|---|
| Any form of aquaculture anywhere in the world | aquaculture OR "fish farm*" OR "shellfish farm*" OR "bivalv* farm" |
| An aim of the study is to determine the suitability of an area for aquaculture | site suitab* OR site select* |
| The study uses GIS to determine site suitability | gis OR "geographic information system" OR model* OR spatial OR "spatial analys*" |
| The study uses the MCE method to determine site suitability | Accounted for when screening the articles |

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indeed diverse methods desirable for our analysis, the paper had to focus on site selection or site suitability assessment for aquaculture and use both GIS and MCE to do so. The keywords used to fulfill these criteria were selected before discussion with a focus group of 6 researchers which confirmed the selection. The keywords used in the database search were aquaculture OR "fish farm*" OR "shellfish farm*" OR "bivalv* farm" AND site suitab* OR site select* AND gis OR "geographic information system" OR model* OR spatial OR "spatial analys*" (Table 1). To prevent the search from being too restrictive MCE was not included in the initial search and was instead considered when screening the articles. The databases used in the search were Scopus and Web of Science because they have the largest number of peer-reviewed articles, as well as ASFA: Aquatic Sciences and Fisheries Abstracts, because it is specific to the subject of interest. This search produced 1493 papers, 495 of which were detected as duplicates, triplicates, or quadruplicates, which left 998 unique papers for screening.

The first round of screening was conducted using the web application Rayyan [35], a tool that supports article screening by multiple users. In this study, three researchers separately performed screening of the 998 records to ensure certainty on the decision to include or exclude a paper. Those papers that resulted in disagreeing opinions or caused uncertainty were then discussed to enable a decision. The second round of screening consisted of reading 207 papers in full to determine whether they should be included in the review. The final number of papers left for review and analysis was 71. Papers were excluded if they did not fit the scope of the study, they were not in English language, they were not in a scientific journal article, or it was not possible to access the paper.

Some of the included articles combined multiple approaches, and therefore contained sections outside the use of MCE and GIS to determine site suitability. In these cases those sections of the paper that were outside the scope of the study were omitted, for example Ferreira et al. [36] investigated farm-scale models for production, environmental impact, and economic performance in addition to their MCE site suitability analysis, data of which were not included in the present analysis.

## 2.2. Data inspection and feature extraction

Key features relevant to the aims of the study were identified (Table 2). Information on each feature was extracted from the 71 papers found via the PRISMA method and the data were recorded in a Microsoft Excel spreadsheet (S1 Appendix). The extracted features were compiled as a database to support their analysis and visualisation with R version 4.1.0 (R Core Team, 2022). R Studio version 220.07.0 (RStudio Team, 2022) and the 'tidyverse' collection of data science R packages [37] were also used.

**Table 2. A list of the features extracted from each article included in the systematic review, grouped by article attributes and briefly described.**

| Group | Feature | Description |
|---|---|---|
| **Article information** | Paper title | Title of the paper |
| | Authors | Authors of the paper |
| | Journal | Scientific journal that published the article |
| | Year published | The year the article was published |
| | Keywords | Keywords listed for the article |
| | Country | Country (or countries) that are covered in the study |
| | Study Area Figure | If the study includes a figure that shows the study area |
| **Study characteristics** | Species | The species that the study focused on (species name) |
| | Species classification | The type of species that the study focused on (e.g., finfish, crustaceans) |
| | Production environment | The type of water in the environment where the study was conducted (e.g., seawater, freshwater, brackishwater) |
| | Production facility | The methods and technology under consideration for use to rear the species |
| **Study design** | Spatial extent | Extent of study area and whether this was within a country, at a national scale, or across multiple countries |
| | Software | Spatial software programs used to analyze the data |
| | Conceptual diagram | The conceptual diagram outlining the model process or model structure |
| | Reclassification | Information on reclassification methods and values |
| | Weighting | Information on weighting methods and values |
| **Data input characteristics** | Data sources identified | Whether the authors reported where their data was retrieved from and how it was collected |
| | Type of input data | If data was collected for the study (primary) or existing data was used in the study (secondary) |
| | Existing data/surveys/reports | Whether existing data from surveys and reports was used in the study |
| | Fieldwork | Whether data obtained from field work was used in the study |
| | Remote sensing | If remote sensing technologies were part of the data collection method and more specifically, which remote sensing satellites were used |
| **Criteria** | Factors | Criteria that influence the suitability of a location for aquaculture and are reclassified to a common scoring system |
| | Constraints | A condition where aquaculture cannot take place |
| | Environmental criteria | Criteria that consider environmental parameters within the production site and/or the surrounding area |
| | Socio-economic criteria | Criteria that consider requirements as a business and/or have an impact on the social relations with the public |
| | Biological criteria | Criteria that consider the biology of the species being farmed or of the species in the surrounding environment |
| | Natural hazards | Whether and which natural hazards were included in the model |
| **Model output** | Resolution | How coarse or fine the spatial resolution of the results are |
| | Seasonal output | If the outputs covered single, seasonal, or multiple times in the year |
| | Scenarios/goals | If there were single or multiple scenarios/goals for the model output |
| | Longevity | Whether future conditions were considered |

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## 2.3. Checklist creation

The analysis in the present study focused on comparing the reviewed article information and reporting, rather than evaluating the quality of the studies as this is subjective between users. The findings were then used to produce straightforward templates (a checklist and reporting framework) to help model developers keep track of the information they should report, facilitate presentation of model details in an accessible format, and allow end users to extract relevant information easily, efficiently, and in a more standardised way. The items on the checklist are a culmination of the various study features reported across the reviewed papers, no additional categories were included. The checklist and reporting framework were designed so they could be included by authors as supplementary materials with their original manuscripts or other dissemination material.

### 2.4. Methodological limitations

The research focused on studies that were published in scientific journals, which were found using the PRISMA 2020 protocol [33,34]. The structured search enabled identification of relevant studies that used MCE in aquaculture site selection modelling. However, systematic searches, although they are more transparent and can be replicated, may lead to bias and omission of studies due to the search criteria used [38,39]. This study focused on peer-reviewed studies, and did not include studies in the grey literature or reports [40], which are often produced by government and not-for-profit organizations [1,41]. Restricting the PRISMA to include articles only in English is a common approach to such analyses, but it is acknowledged this was a limitation and may have missed relevant studies.

Data was extracted manually from each study because it is recognized that inconsistent terminology and lack of standardised reporting is a constraint for automated information extraction [42,43]. However, manual data extraction also has problems, as some of the information may have been missed, overinterpreted, or miscategorised due to the subjective nature of reading and processing text [44]. That being said, the challenges in extracting information also support the need for a checklist and datasheet that will allow end users to easily extract key information about a model or use as a common framework to compare with other models.

## 3. Results

### 3.1. Article information

The 71 articles included in the analysis covered 31 countries across the globe, with India (n = 11), Japan (n = 8) and Iran (n = 7) occurring most frequently (Fig 3). Almost all the studies (n = 67) included a study area map before the results section to provide context on the location, however the level of information given in the study area maps varied. While some maps only showed the study area, others provided additional information such as sampling locations

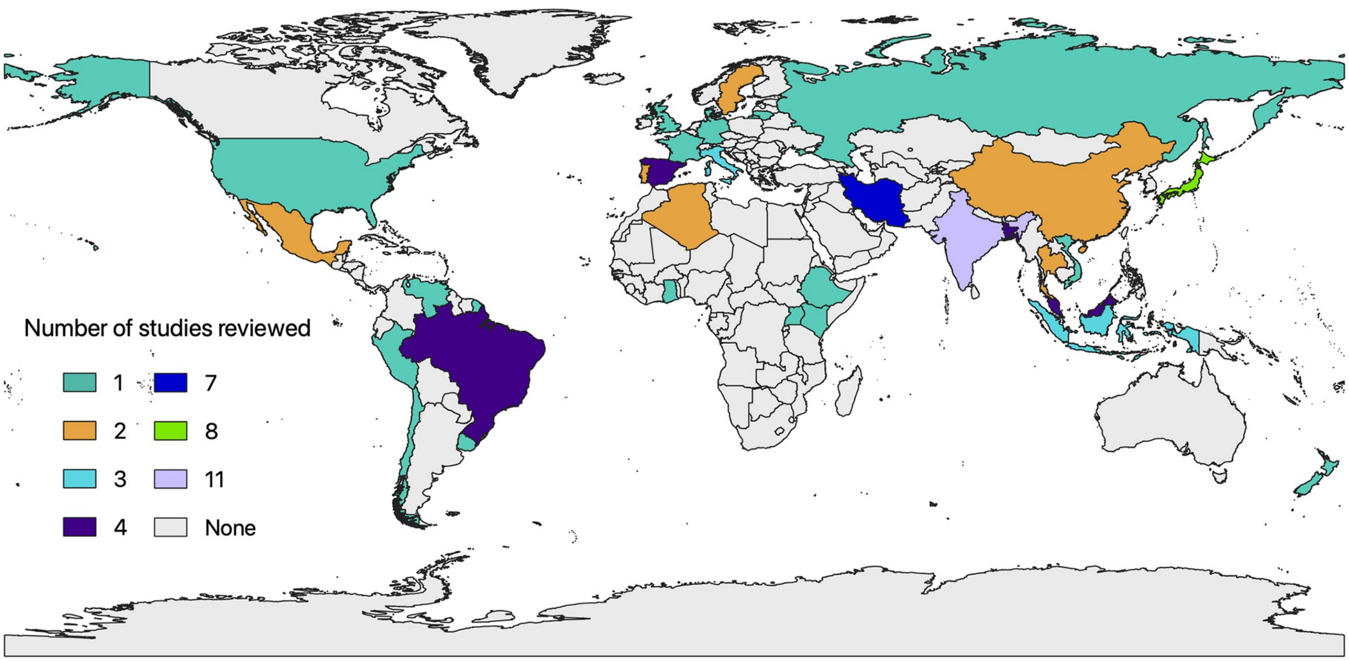


**Fig 3. Geographic distribution of the 71 articles analysed in this research.** Created with QGIS Version 3.26 using the base map layer provided by Natural Earth (found at https://www.naturalearthdata.com/downloads/10m-cultural-vectors/).

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and physical characteristics like topography and depth. Though difficult to quantify as interpretation can be subjective, it was easier to comprehend some maps compared to others, and similarly, poor figure quality resolution in print or on-screen was an issue for some.

The articles were published in the years between 1995 and 2022, with the majority of articles (n = 58) published in 2010 or later. However, the publication date is only a general indication of when the study was conducted, and in some cases, it was difficult to tell how up to date the input data and the model outputs were.

## 3.2. Study characteristics within the analysed articles

The studies covered a range of species, production environments and production facilities. Most studies investigated suitable areas for the marine environment (n = 31) but freshwater (n = 15) and brackishwater (n = 13) production environments were considered as well. A few studies considered multiple production environments (n = 4). Only one considered saline groundwater. There were 4 studies where the production environment was unclear, e.g., they considered transitional areas like estuaries, and 3 studies that did not specify a production environment.

There were 45 studies that identified specific species, whereas 12 studies used a more generic species name (e.g., 'tilapia'), and 10 studies used very broad groupings (e.g., 'fish' or 'shrimp'). Finfish (n = 28) were the animals considered most, but bivalves (n = 17) and crustaceans (n = 13) were also represented in the literature. In contrast, relatively few studies considered seaweed (n = 4) and echinoderms (n = 1). There were 3 studies that did not specify any species or group, instead they investigated suitability for aquaculture with a broad sense where no species requirements were considered. One study evaluated suitability for more than one named species.

The production facility investigated also varied with the production environment. In marine studies, the most common methods were cage aquaculture (n = 11, 35% of marine studies) and suspended culture (n = 11, 35% of marine studies). For freshwater studies, most investigated pond aquaculture (n = 10, 67% of freshwater studies), while few focused on cage aquaculture (n = 3, 20% of freshwater studies). For brackishwater studies, pond aquaculture (n = 8, 62% of brackishwater studies) was the most common. Across all three production environments, about one fifth of studies failed to specify which production facility the study was intended for (n = 13, 18%).

## 3.3. Study design within the analysed articles

Most of the studies investigated a specific area at the sub-national scale (n = 63), but there were also a small number of national (n = 4) and international (n = 4) studies. Two of the international studies focussed on areas bordered by multiple countries while the other two investigated two distinct study areas from different countries that were important for production of the species and for the country.

Information on the software used was provided by most studies (n = 62). ArcGIS or related Arc programs were the most commonly used (n = 41), followed by IDRISI (now known as TerrSet) (n = 9). There were 9 studies that did not report the software used in the analysis. Four studies used multiple software or programming packages for different aspects of the study, such as data processing, modelling, and visualisation.

Many studies (n = 62) used some sort of conceptual diagram or schematic to outline the modelling process or the model structure. However, there was no consistency in the design or presentation of the figure. As with the study area figures (Section 3.1.), some figures were easier to understand than others and the amount of information conveyed in the figure was highly variable between studies.

Descriptions of the methods and models varied considerably between studies. The research articles had different structures, sections, and writing styles, which caused some challenges in extracting information on the model structure and methodology. A range of approaches were used for reclassification (e.g., Boolean, crisp boundaries, fuzzy) and determining weights. There were 24 studies that provided no or limited information on reclassification scores, and 13 studies that had no or limited information on the assigned weights. This included studies that referred readers to other sources, for example because they followed the same scheme as a previously published article. Some studies provided information on reclassification but not weighting, and vice versa, while others omitted both. However, it was possible to recognize that the most common approach to combining layers was the Weighted Linear Combination (WLC). This means that the weight assigned to a factor determines its extent of trade-off relative to other factors. The WLC allows a continuum between no trade-off and full trade-off for each pixel within the spatial map.

## 3.4. Data input characteristics within the analysed articles

As with other aspects of the methodology, there were different ways of presenting information on the input data, including text descriptions, tables, and figures. There was no consistent approach, and some studies provided more information than others. It was estimated that 34 studies clearly identified the data sources, 28 studies partially identified the data sources, and 10 studies did not identify data sources. The mentioned data were from a range of primary and secondary sources. Popular sources of data and information included existing datasets, maps, reports (n = 64) and field work conducted within the study (n = 28). There were different levels of detail included in the reporting of processing required, and the initial format and resolution of the input data.

Over half of the studies used data collected via remote sensing technology (n = 42). Satellites mentioned included NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) (n = 12), NASA/USGS's LANDSAT (n = 8), and the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observation Satellite (ALOS) (n = 5). The data was used for a range of spatial layers, for example land use, sea surface temperature, soil quality, water sources and market location. Other data layers may also have been derived from remote sensing technology without specific mention in the papers. Some of the authors did their own analysis while others accessed prepared data layers from databases.

## 3.5. Criteria within the analysed articles

The number and type of criteria used for the MCE method varied substantially between the studies. Ecological criteria were commonly incorporated in the MCE method for studies using GIS to determine areas suitable for aquaculture (Fig 4). Of the 71 studies, 70 included ecological criteria. Physical (n = 57), chemical (n = 39), and biological (n = 30) water parameters were popular to include in studies, along with bathymetry (n = 33) and physical soil parameters (n = 33). Socio-economic criteria were also commonly incorporated as 60 of the studies included their use. Infrastructure (n = 55) was the most frequent socio-economic criteria included, with non-aquaculture land use (n = 31) being the second most common criteria for inclusion. Biological criteria on the other hand were not often used in the studies to date as only 7 included these criteria. Of the studies that included biological criteria, health risk (n = 3) and growth potential (n = 3) were evaluated most frequently. In some cases, there was a description of the criteria and an explanation of why the criteria were chosen for the study, but

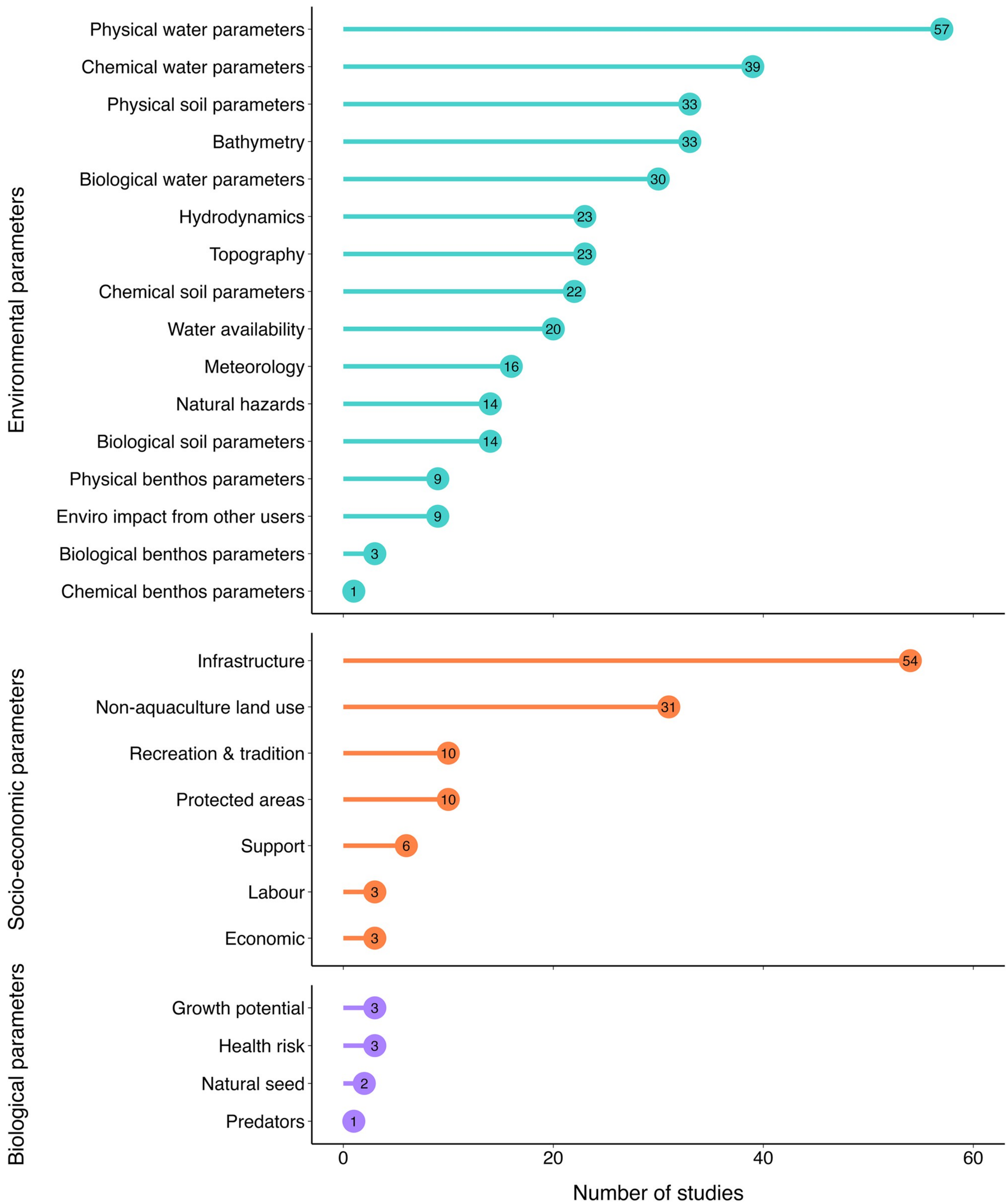


**Fig 4. The frequency at which various ecological, socio-economic, and biological criteria were included in the MCE analyses for site suitability studies using spatial modelling.**

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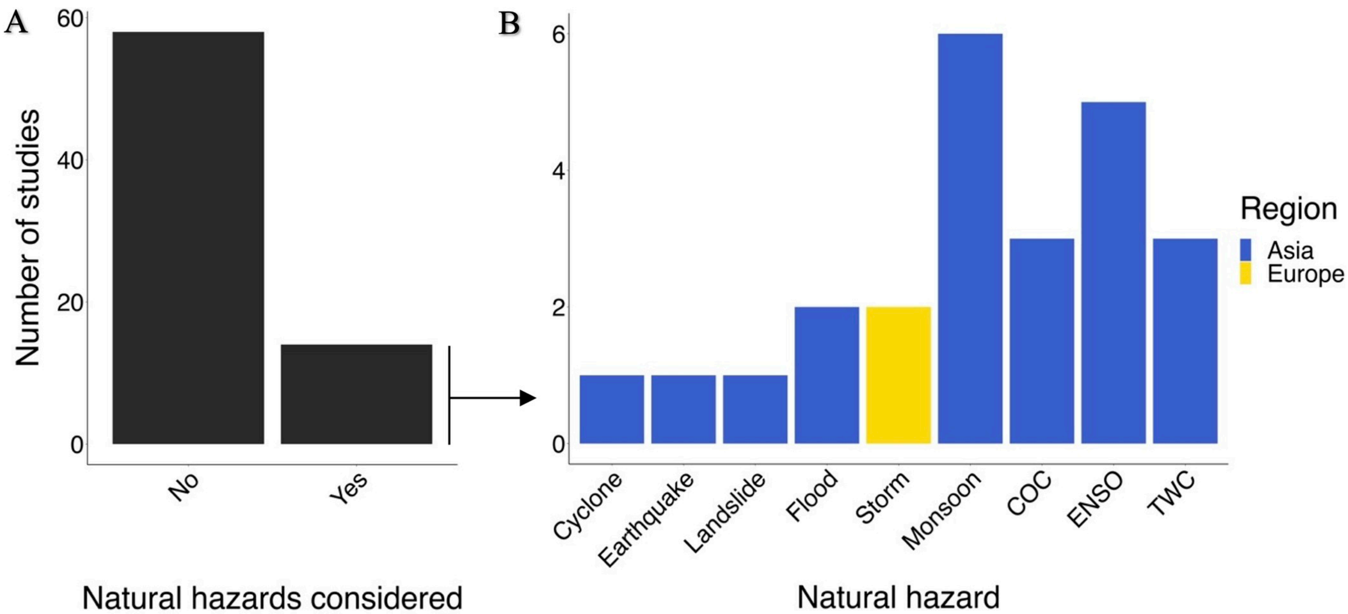


**Fig 5.** A) The number of studies that considered natural hazards and inter-annual climatic variations in the MCE analysis and B) the number of studies that considered a range of natural hazards and inter-annual variations in climate, where COC = Coastal Oyashio Current, ENSO = El Niño and/or El Niña oscillations, and TWC = Tsugaru Warm Current. The colours of the bars represent the region in which the study was conducted. Some studies considered more than one natural hazard, resulting in a tally for figure B) that surpasses the number of papers that considered natural hazards as seen in figure A).

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this was not consistent. Although criteria were most often selected based on their relevance for the overall study goal, the selection and omission of criteria was sometimes due to the availability and quality of datasets since not all studies and areas have access to data for all criteria, so the ability to generate new data layers may be limited by resources or the scale of the study. Some types of criteria were more frequently included than others, but there were no universally included criteria across all studies.

Few studies considered the effects of natural hazards and inter-annual climate variations on the suitability of areas for aquaculture (n = 14) (Fig 5). Those that did consider extreme events conducted their studies either in Asia (n = 12) or Europe (n = 2), and the most frequently investigated events were monsoons (n = 6) and ENSO events (n = 5). It was mainly studies conducted in the marine environment (n = 11) that considered these extreme events, but some brackishwater (n = 2) and freshwater (n = 1) studies considered them too.

## 3.6. Model output characteristics within the analysed articles

The term spatial resolution is used here to refer to the size of the grid cell or pixel in the output layers. The input layers may have different resolutions but are resampled to the same resolution for the output. Over two thirds of the studies (n = 49) failed to report the spatial resolution. Of the studies conducted for each of the three production environments, 33.3% reported their final output resolution.

Most studies produced a single time-related output (n = 59), including those studies that used data from one point in time and those that averaged data over a period of time. Fewer studies produced seasonal (n = 9) and monthly (n = 3) outputs. However, some studies (n = 21) provided multiple outputs covering different scenarios, e.g. (different species). Only one study considered potential future conditions under climate change.

### 3.7. Checklist and reporting framework

Table 3 presents the checklist developed in the present study resulting from the inconsistencies observed in documentation with respect to the features analysed in each section. The checklist provides an overview of the steps and details to be included in GIS MCE site suitability and site selection studies for aquaculture. The checklist is designed to be used by authors during manuscript preparation and practitioners looking to implement a model under real-world circumstance. Authors can complete the checklist provided as an Excel worksheet in S2 Appendix and append to their original manuscript before submission.

**Table 3. Comprehensive checklist of steps and details to be included in MCE site suitability studies for aquaculture.**

***Checklist for reporting aquaculture site selection studies***

| Section | Feature | Response | Justify, if not or partially done |
|---|---|---|---|
| Study characteristics | The study area name is stated in the manuscript title and/or abstract | Yes / No | [insert text to explain] |
| | The study area figure is included and clearly labelled | | |
| | The target species is/are clearly identified | | |
| | The production environment and facility are described appropriately | | |
| | A description of the study area as well as its relevant features are included | | |
| Study design | The spatial extent of the study is clear | | |
| | A well-illustrated conceptual diagram is included | | |
| | The logic for selecting suitability criteria (factors and constraints) is explained, in addition to the intentional exclusion of certain criteria | | |
| | Model design reflects what type of site selection scenarios can be tested e.g., season, target species, cage size, etc. | | |
| | All software and versions used are clearly written | | |
| | Method used to reclassify criteria and details of their suitability/classification values are given | | |
| | Criteria weights are clear, including the methods for assigning these | | |
| Data input characteristics | All sources of data have been acknowledged | | |
| | The versions of datasets used or year of data collection is shown | | |
| | Difference is clear between primary and secondary data | | |
| | It is easy to understand how primary data were collected and processed | | |
| | It is easy to identify the categories of secondary data sources e.g., Online database, Google Earth, Model run, etc. | | |
| | If applicable, the remote sensing organization/satellite that provided data is clearly written | | |
| | The original coordinate reference system of data is given, including any reprojection | | |
| | The spatial and temporal resolutions of data are detailed, including any modification | | |
| | It is clear whether the data used was existing or produced from a model to predict future conditions | | |
| Criteria | Includes descriptions and explanations if the factors have been organised into groups and sub-models | | |
| | Constraints have been clearly identified | | |
| | It is easy to identify input data that served as both factor(s) and constraint(s) | | |
| | The method of combining input data into final output(s) is sufficiently described | | |
| Model output | Where applicable, all submodel outputs are clearly presented | | |
| | The overall suitability/site selection model(s) outputs are clearly presented | | |
| | The overall suitability/site selection model(s) show areas identified as constraints | | |
| | Spatial and temporal resolution of the submodel(s) and final model outputs are clearly stated | | |
| | Where different scenarios/goals were modelled, these are adequately described | | |
| | It is clear if model(s) were applied to identify specific sites through a participatory GIS exercise or other means | | |
| | Potential applications and limitations in real-world practice within and outside the study area are explained | | |
| | Link to model output if available | | |

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**Table 4. Reporting documentation template for the GIS-based MCE aquaculture site selection model.**

| | |
|---|---|
| Article/document title | |
| Software and version | |
| Spatial extent of study | ☒ Area within one country<br>☒ National<br>☒ Multi-national |
| Country/ Countries | |
| Species<br>(If more than one species add a new row) | Scientific name:<br>Common name:<br>Other names: |
| Production Environment | ☒ Marine ☒ Brackishwater<br>☒ Freshwater ☒ Other: |
| Production system | ☒ Cages ☒ Tanks ☒ Ponds ☒ Raceways<br>☒ Recirculating Aquaculture System (RAS)<br>☒ Suspended culture ☒ Bottom culture ☒ Integrated multi-trophic aquaculture<br>☒ Other: |
| Suitability criteria (Layers used in the model) | Factors:<br>Constraints:<br>Both a factor & constraint: |
| Reclassification method | ☒ Boolean ☒ Crisp ☒ Fuzzy |
| Model output | ☒ A single suitability map<br>☒ Seasonal suitability maps<br>☒ Suitability maps for different scenarios<br>☒ Other |
| Spatial resolution of output | |
| Temporal resolution of output | |
| Other relevant comments | |

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In addition to the checklist, a two-part documentation template was produced to aid end users in the extraction of key information. While the checklist provides steps to guide reporting within an article or report, the reporting documentation is intended to be included as supplementary material which could be reviewed by end users prior to reading the study to quickly identify fundamental characteristics of the study and determine whether the research is relevant for their application. It is still important to refer to the study for more complete explanations and background if users identify it as being useful based off the documentation tool. The complementary approach of checklist and documentation template represent a reporting framework that can better support communication of key model characteristics to any end user. The documentation template is divided into two parts; the first outlines the key characteristics of the model(s) (Table 4) and the second is used to show important information about the data inputs (Table 5). The documentation template is an easily accessible overview of key features and is added value to a study where the details are included in the main text of the article. The documentation template is provided in S3 Appendix.

## 4. Discussion

The use of spatial models for aquaculture site suitability assessment has been increasing over time and is widely recognised as an important approach for aquaculture planning and

**Table 5. Reporting documentation template for data used within the GIS based MCE aquaculture site selection model (new row inserted for each data layer).**

| Data layer | Year | Primary / secondary data | Coordinate reference system | Spatial resolution | Temporal resolution (e.g., daily, monthly, annual) | Link to original data source (if relevant) |
|---|---|---|---|---|---|---|

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management. GIS-based MCE models are particularly useful as they can be used to integrate multiple factors from a range of data-sources and produce outcomes that would otherwise be difficult to show [9]. Data analysis conducted in this study has revealed the inconsistencies in reporting across site selection studies, emphasizing the importance of a checklist to enhance the quality, transparency, and therefore real-world useability of the reported results. The ability of the checklist to make such studies accessible for use as decision making tools for end users reforms the approach to planning by improving the longevity of the decisions made during the initial planning stage, and therefore the sustainability of the sector.

## 4.1. Studies used in the analysis

We analyzed 71 scientific articles found using the PRISMA systematic review method, which produced a wide range of studies. The studies, which are listed in S1 Appendix, had wide coverage of different types of global aquaculture, including oyster culture in Venezuela [45], shrimp farming in Vietnam [46], mussel production in Italy [26], scallop in Japan [29], sturgeon in Iran [47], tilapia in Ethiopia [48], tilapia in Kenya [49], rainbow trout in Peru [50], and macroalgae in Sweden [51]. Given the range of different species, aquaculture systems, locations, and production environments covered, the 71 studies were considered an appropriate sample to obtain an overview of trends and look at how methods and results are presented. It is acknowledged that excluding grey literature and limiting the search to peer-reviewed articles in the English language may have introduced bias in the results.

## 4.2. Model characteristics and available information

Extraction of information from the studies was challenging. Across the 71 articles, there was no consistent approach in reporting the model structure, data inputs, methodology, or outputs. Sometimes information was reported using tables or figures, while on other occasions it was through narrative text. The way in which information is presented and the amount of detail reported in scientific studies is not necessarily an indicator of quality of the study or model, as writing styles are highly variable and journal requirements can also have strict word limits and restrictions on the number of figures and tables allowed. The challenges encountered in the present study are likely to be similar to those of end users who wish to find details on the model, reinforcing the need for more standardised approaches to reporting.

Multiple studies omitted information pertaining to how the study was conducted, for example the spatial modelling software used, the origin of input data, and the method of weighting criteria. Missing or incomplete information can make it difficult to interpret the results and replicate studies. These findings follow broader concerns that there is a reproducibility crisis in GIS studies [52,53].

Information that are key to the applicability of models and outputs to real-world circumstance were also absent in some studies, the first being vagueness on the production system for which the study was intended. Aquaculture is a broad term that covers many different production systems and species [54], each of which have different requirements, thus it was surprising that some studies did not target a particular species and system. In some cases, the target species, production environment and system can be inferred, but this could lead to an erroneous interpretation of the results. Likewise, there was also a lack of clarity in some studies on which criteria were considered in the analysis to produce the site suitability output, or which were intentionally excluded. Studies evaluating the suitability of aquaculture for different species and production systems in different locations will inherently require the consideration of different criteria, as was shown by the lack of any universally included criteria and the breadth of criteria used across the studies. Since there are a vast number of criteria that can be included in a site selection study and because each study will include only the most applicable criteria or the criteria for which data is available, it is crucial that authors explicitly state the criteria and input data that were used to produce the model output. The final resolution of the output was also underreported. Without knowledge of the resolution, the usefulness of the study for application to an area cannot be understood [12]. It is often also important to understand what input data were resampled, as resampling method can impact accuracy [55]. The inclusion of and clarity on the features discussed in the studies was not consistent across the reviewed papers, showcasing how it may be difficult for end users to interpret results and apply them to their own evaluations, emphasizing the need for a checklist to ensure relevant information is included in site selection studies.

Whether it was a single, monthly, or seasonal set of conditions used for input data, the majority of studies focused on whether areas had potential for aquaculture according to current environmental, socio-economic, and biological criteria. Few studies considered climate change, and only one study [29] included layers with potential future conditions. Climate change is expected to have considerable impacts across the aquaculture sector [56], which may in turn affect the suitability of areas for aquaculture. Performing studies with climate-conscious spatial management approaches can provide a means of reducing industry vulnerability to the risks of climate change and promote adaptation to new conditions [1]. However, there are also challenges in evaluating how the suitability of a location may change as many impacts will be site specific [57] and there is a lack of information on how the climate is changing at a local scale [58]. Even so, it may be useful if model developers include a statement on the potential longevity of the results. Clarity on longevity of the data and results is not just relevant for climate change, but other factors such as social and economic data which change over time. It is not sufficient to rely solely on the year of publication as there can be a considerable time spent across different stages; data collection and processing, model development, and writing the paper and publishing results. Accordingly, it would be useful to include a table that outlines the raw data in the study, as well as the source of the data and the year the data layer was from, as was done in the study by Aghmashhadi et al. [59]. For this reason, we have produced Table 5 as part of the reporting framework.

Most studies used data exemplifying "typical" conditions, that is they neglected to consider potential impacts from natural hazards and inter-annual variation in the climate system, such as ENSO events. This likely is in part due to the varying locations of the studies. Different regions are subject to different levels of risk to extreme weather events [60], and therefore inclusion of these criteria are not necessarily warranted for every analysis. Their inclusion, however, may have been overlooked because such extreme events do not frequently occur. Nevertheless, if omitted because such events are rare or there is little data available, it may still be useful to explain in the model description that the model represents typical conditions rather than all conditions the area may experience.

## 4.3. Checklist and documentation to support use of models for real-world decisions

Checklists are emerging as an important transparency tool in many research areas [61–63]. The major advantage of a checklist is that it provides a way of ensuring all necessary information is covered to enable reproducibility by researchers and effective model application by practitioners. Efforts to increase transparency are essential in addressing major societal challenges such as increasing food production in a responsible manner. Decision makers must be able to justify actions taken, especially within complex circumstances where there are trade-offs between a range of environmental, social and economic factors [64]. The checklist and reporting framework developed in this study provide a clearer approach to reporting models within scientific studies and a more efficient way for stakeholders to access information on the model characteristics. However, the checklist and reporting framework are not replacements for geographic information metadata, which also has an important role to play in GIS documentation [65].

The checklist presented here was deliberately designed to ensure that authors are communicating information that is useful for understanding the model and how the results can be used to help with real-world aquaculture planning decisions. Other aquaculture related studies have developed checklists for a range of purposes; encouraging best practice in use of environmental chemicals [66], guidance in designing and implementing disease surveillance programmes [67], and assessment of site characteristics for open-ocean aquaculture [68]. In other sectors, checklists have been used to evaluate geoportals used for sustainable tourism planning and management [69], to report species distribution modelling for conservation management [70], and to assess learning analytics dashboards in higher education [71]. Checklists can help address challenges in communication between groups with different expertise, such as modellers and practitioners. Similar to the intention with the present study, Wright et al. [72] developed a checklist in an attempt to bridge the gap between science and action in the conservation sector, outlining key points that would improve decision-making in a complex topic that spans biological, economic, social and environmental issues. These checklist approaches align with increasing recognition that transformative sustainability actions will only occur if decision support tools are made more accessible and communicated more effectively to end users [73].

The proposed documentation template goes further than a checklist as it not only reminds the model developer what information are necessary to report, it also provides a format in which it can be delivered. The template is flexible, and it can be adapted to include additional considerations deemed important for understanding a model. However, caution is advised as too many modifications or omissions of the original checklist and reporting structure could undermine the ability to produce consistent and comparable documentation, which was one of the key drivers for the template in the first instance. Although developed for GIS-based MCE studies, the checklist and reporting framework presented in this study can also be adapted for other aquaculture modelling studies. Likewise, use of a standardised checklist and improved reporting could also be a move towards addressing the reproducibility crisis [52, 53], as suggested by Feng et al. [74] for ecological niche modelling.

In practice, the checklist and reporting framework should be relatively straightforward to complete, and the documentation could also be translated in other languages, thus enhancing the reach of the study and facilitating access to more stakeholders and potential users of the information. Under some circumstances, checklists and standardised reporting frameworks may be seen as a constraint that misses context-specific information and relevant details [75], but it is important to stress that the checklist and reporting framework presented here is intended as a supplement to the normal presentations, reports and scientific papers in which further information is given, providing added value rather than replacing other forms of communication. The checklist and reporting framework presented here are a useful way to enhance the usability of GIS-based MCE models in the sustainable development and management of aquaculture worldwide.

## 5. Conclusion

The world is facing major societal challenges, including climate change and food nutrition security, so aquaculture, like all industries, must aim for sustainable and responsible practices through transformative actions that will maximise benefits and minimize negative impacts.

Key to aquaculture sustainability is a suitable location, but site selection involves trade-offs between environmental, socio-economic, and biological factors. The usefulness of GIS-based site selection studies is well-recognised for aquaculture, but there is still a gap between model development and use for real-world planning and management decisions. It is important to identify ways to bridge this gap, remove potential barriers, and increase usability and acceptance of GIS models by all relevant stakeholders within the aquaculture sector. This study has shown that there is a need for standardised reporting and model documentation to improve communication with end users. The analysis has revealed that there are inconsistencies in the information provided and often incomplete descriptions of data inputs and model characteristics. Lack of transparency in the modelling approach can make it challenging for end users to understand the strengths and limitations of the model and its outputs. Furthermore, missing or unclear information may lead to inappropriate decisions like development in locations inferior to other possibilities or overlooking locations with potential. Hence, insufficient documentation and unclear reporting could affect progress towards a more sustainable aquaculture sector, missing opportunities to contribute to key sustainable development goals and long-term societal benefits.

The checklist and reporting framework developed in this study can be completed by model developers and can be included alongside a model in peer-review publications, reports, and other dissemination material so that important information is available in an accessible format to end users. Thereby, the checklist and reporting framework provide a more standardised approach to reporting the characteristics of the model and outputs, helping to bridge the gap between research and real-world application, which will allow end users to make the most sustainable decisions relevant to their aquaculture system. The checklist and reporting framework offer a new way to support communication in a structured way, with end users able to clearly outline the important aspects of the data, model and outputs, and explain the rationale behind decisions made based on the model results. The increased transparency offered through this approach can help build trust in the decision-making process, which is particularly important when communicating with people not involved in the model development. This study has focused on aquaculture, but the recommendations are relevant across all sectors that are using data, models, and tools to make decisions in an increasingly complex world. The global population is facing major societal challenges and transformative action must be supported by clear evidence and a transparent pathway towards choices made.

## Supporting information

**S1 Appendix. Data extraction from the 71 studies reviewed.**
(XLSX)

**S2 Appendix. Comprehensive checklist of steps and details to be included in MCE site suitability studies for aquaculture.**
(XLSX)

**S3 Appendix. Model documentation template for aquaculture site selection studies.**
(DOCX)

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